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INTRODUCTION

The requirement to measure flight loads on aircraft flying at supersonic and hypersonic speeds led to the construction of a facility for calibrating strain gage installations to measure loads in an elevated temperature environment (ref. 1). Measuring loads in an elevated temperature environment with strain gages (refs. 2 and 3) requires the ability to heat and load aircraft under simulated flight conditions.

This paper describes the Flight Loads Research Facility (FLRF) at the NASA Dryden Flight Research Facility at Edwards, California. The Flight Loads Research Facility has the ability to test structural components and complete vehicles under the combined effects of loads and temperatures, and to calibrate and evaluate flight load instrumentation under the conditions expected in flight. The laboratory provides close support of flight-to-flight program planning by permitting structural-integrity testing, instrumentation calibrations, ground vibration tests, and the analysis of unexpected problems encountered in the course of exploratory flights.

SYMBOLS

C	acquired transducer output, data counts
C_I	initial (ambient) transducer output, data counts
EU	calculated engineering unit value
EU_I	engineering unit value when $C = C_I$
EU_0	$= EU_I - \frac{\Delta EU}{\Delta C} C_I$, engineering unit value when $C = 0$
$\frac{\Delta EU}{\Delta C}$	change in transducer engineering unit output associated with unit change in transducer data count output, calculated by the calibration program
K_1, K_2	calculated control parameters
P_n	rate multiplier power level command for n^{th} control period, 0 to 63

R rate multiplier input pulse rate, pulses/sec

T_n feedback thermocouple output at the end of the n^{th} control period, data counts

$\grave{T}_n$ desired feedback thermocouple output at the end of the n^{th} control period, data counts

T_0 initial feedback thermocouple output, data counts

t_n time at the end of the n^{th} control period, sec

GENERAL DESCRIPTION

The Facility (fig. 1) is located in a hangar-type structure with a small shop and office area attached to one end to accommodate the operations staff. It is located adjacent to Rogers Dry Lake and is connected to the dry lake and the Edwards Air Force Base runways by a ramp and taxiway. A 929-square-meter (10,000-square-foot) storage area is attached to one side for the storage of equipment and supplies.

Hangar Test Area

Figure 2 is a sketch of the building layout. The hangar-door opening is 12.2 meters (40 feet) high and 41.6 meters (136 feet) wide Additional access to the test area from the exterior is provided by personnel doors and an equipment door. Access to the test area from the shop area is provided by two equipment doors. The unobstructed test area is 41.5 meters (150 feet) long, 36.5 meters (120 feet) wide, and 12.2 meters (40 feet) high. There are 18 tiedown slots spaced 1.8 meters (6 feet) apart, 7 instrument wire trenches, 8 electrical power trenches, and 5 trenches for the distribution of shop air and hydraulic power.

The cross-sectional dimensions of the trenches are 25.4 centimeters (10 inches) by 30.5 centimeters (12 inches). The mechanical trenches distribute hydraulic power, water, and compressed air to the test area. The maximum load capability of the tiedown slots is 67,000 newtons (15,000 pounds) of uplift every 0.6 meter (2 feet). Figure 3 shows a sketch of a typical tiedown slot. A 44,000-newton (5-ton) overhead crane services the entire hangar test area. Figure 4 is a photograph showing a portion of the interior of the hangar test area.

Control Room

The control room (fig. 5), which contains the data acquisition system and the control systems for the heating and loading equipment, is on the second

floor. Two observation windows 3.4 meters (11 feet) wide and 1.2 meters (4 feet) high and a closed-circuit television system are provided for visually monitoring the hangar test area. The television system has three cameras which can be positioned in the hangar test area. One can be controlled remotely from the control room for tilt, pan, elevation, focus, and zoom. There is two-channel intercommunication system between the control room and the 12 sites of the data acquisition system in the hangar test area.

Power Distribution

Twenty megawatts of 480-volt, three-phase 60-cycle power are available for distribution to 512 power control channels. Approximately 2.3 megawatts of 480-volt, three-phase 60-cycle power are available for distribution to 24 analog phase control ignition power regulators. The electrical power substation is located adjacent to the hangar test area, as indicated in figure 2.

Hydraulic power consists of a 0.63-liter-per-second (10-gallon perminute) supply operated at 20.7 meganewtons per square meter (3000 pounds per square inch). Compressed air is supplied by a 93,200-watt (125-horsepower) compressor capable of delivering 0.598 cubic meter per second (845 cubic feet per minute) at 413.7 kilonewtons per square meter (60 pounds per square inch).

EQUIPMENT CONFIGURATION AND CAPABILITIES

The following outline lists the major pieces of equipment used to accomplish various tasks. Later sections of the report describe in detail the configuration and capability of each item of equipment.

- Data acquisition system (1000 channels at 10 samples/channel/sec.)
- Digital thermal load control system (512 channels)
- Analog thermal load control system (28 channels)
- Analog electrohydraulic load control system (28 channels)
- Air operated hydraulic loading system (2 channels)
- Ground vibration test system (4 channels)
- Universal testing machines (3 channels)
- Ovens (7)
- Communication system
- Moment of inertia equipment
- Shop equipment

- Liquid nitrogen (2 tanks)
- Structural erector set

Data Acquisition and Digital Thermal Load Control System

The laboratory data acquisition system is an addressable, gain-programmable, self-calibrating system. The sampling and analog input sensitivity of each data channel are computer commanded.

Figure 6 shows the salient features of the laboratory data acquisition and control system (DACS). A digital computer is the central part of the system. The computer is a 16-bit integer-arithmetic processor with 32,768 words of memory and a memory cycle time of 750 nanoseconds. In addition to standard input/output capability, the computer has eight direct memory access controllers that allow the efficient input or output of large blocks of data. A number of computer peripherals not shown in the figure are listed below.

- Acquisition site calibration control
- Acquisition site interface
- Acquisition sites (10)
- Card reader
- Graphics display
- Digital computer
- Digital input/output controller
- Digitally programmable oscillator
- Digital power controllers (29)
- Digital-to-analog outputs (48)
- Fixed-head disk
- IRIG B time code reader
- Line printer
- Magnetic tape controllers (2)
- Magnetic tape units (3)

* Operator control console

* Paper tape reader/punch

* Rate multipliers (512)

* Teletypewriters (2)

* Television-compatible alphanumeric display

* Strip chart recorders (24 channels)

Acquisition sites. - The hardware necessary to condition, calibrate, sample, amplify, and perform the analog-to-digital conversion of transducer output exists in 10 data acquisition sites, each of which accommodates 100 transducers. The sites are placed near the test specimen to minimize the length of the low level signal lines. The data acquisition sites communicate with the computer through an acquisition site/computer interface in the control room.

The data acquisition sites (fig. 7) receive sampling commands containing channel and gain information from the acquisition site interface. Nominal low level input sensitivities are ±5 millivolts, ±10 millivolts, ±20 millivolts, ±40 millivolts, and ±80 millivolts full scale. The high level channel input range is fixed at 0 volt to 4 volts full scale. Low level transducer signals are conditioned and multiplexed into the data amplifier, where they are amplified according to the gain commanded. The amplifier output, or the output of the high level multiplexer, is converted to 12-bit binary data by the analog-to-digital converter and sent to the acquisition site interface.

The data acquisition sites also contain the calibration circuitry necessary to calibrate and verify the proper operation of the transducer/ data channel combination. A voltage substitution calibrator is used to substitute 0 millivolt, ±4 millivolts, ±8 millivolts, ±16 millivolts, ±32 millivolts, and ±64 millivolts for the transducer signals. In addition, the signal conditioning for each channel contains relays for imposing transducer calibrations, disconnecting the transducer excitation voltage, and shorting the signal conditioning input connections. Calibration signals can be imposed through local control switches, or they can be commanded by the computer.

Acquisition interface. - The acquisition site interface (fig. 8) performs a number of functions. Data channel sampling rate is controlled by the computer through a programmable oscillator. The sampling command for each data channel is sent to the interface by the computer. The acquisition interface identifies the site to be sampled and sends it channel and input sensitivity, or gain, information. The gain is stored in the interface so it can be used to scale the returning data from the commanded channel.

A data channel can produce nonzero digital data when its analog input is 0 volt. This bias, called zero offset, is used to correct the data. In addition to sampling commands, the computer sends the interface a zero offset

correction for each sampled channel. The interface adds this correction to the transducer output data, which have been previously scaled, and sends the sum to the computer. Thus, the data arriving at the computer appear as though they had been sampled on a single gain and accurately zeroed. The data can be used for temperature control or display calculations without further correction.

The data acquisition site interface also performs two checks on the validity of the data. If the data are off-scale because of analog-to-digital converter saturation or offset adder overflow, the interface informs the computer via a priority interrupt. The data acquisition program then decreases the input sensitivity of the off-scale data channel in order to reestablish data validity.

The origin of the data is identified only by the order of the data channel sampling commands. Therefore, if synchronism is lost between the sampling commands and the data, the identity of the data is lost. The data acquisition site interface contains the logic to detect this condition and inform the data acquisition program for corrective action.

Digital temperature control equipment. - Each power control channel consists of a rate multiplier, a power controller, and a zone heater. The function of the rate multiplier (fig. 9) is to provide digital control of the power supplied to the radiant heater. To accomplish this, the rate multiplier commands the power controller to conduct or block the conduction of complete 480 Vac power line cycles to the heater. The 60-hertz power line frequency is divided by a 63:1 binary counter. The outputs of the counter stages are logically ANDed with the contents of the 6-bit power command register, which contains the computer-supplied power level command. The results of the ANDing are logically ORed to produce power controller firing commands.

The power level command, which can be any number from 0 to 63, can be thought of as the numerator of a fraction that has a denominator of 63. This fraction multiplies the power line cycle rate (fig. 10). If, for example, the power level command is 1, the multiplier issues one firing command per 63 power line cycles; if the level commanded is 63, the rate multiplier issues a firing command for every power line cycle. The rate multiplier design is such that the firing command pulse stream produced for a given power level command is as nearly periodic as possible.

The rate multipliers have an automatic test capability. The computer can command a given power level, send pulses to the binary counter, and count the number of resulting firing commands to check the operation of the rate multiplier. The testing can be performed without applying power to the zone heaters. In addition, each rate multiplier compares the firing commands it generates with firing occurrence signals from its power controller. If the power controller is conducting more or fewer power cycles than commanded, an error indication is sent to the computer. Finally, the flow of power level commands to the rate multipliers is monitored by a watchdog timer. If the flow of commands from the computer stops for more than 1.5 seconds, the watchdog terminates the application of power to all the heaters. This minimizes the possibility of test specimen damage due to computer failure.

The power controllers (fig. 11) conduct one power line cycle for each rate multiplier command. To minimize electromagnetic interference in the data acquisition system, conduction is begun as the power line voltage passes through 0 (zero crossover). The power controllers are arranged in groups of 18 controllers per cabinet. The controllers in any given cabinet are connected, six per phase, to three-phase 480 Vac through a common circuit breaker. The circuit breakers can be opened from the control room either manually or under the computer control. A fault detection circuit was built into each power controller to sense leakage currents between heaters or between a heater and electrical ground, identify the power controller involved, and open the circuit breaker of the affected power controller cabinet. External equipment not shown in figure 6 signals the computer if any breaker opens. If any breaker opens, all breakers will open simultaneously.

Operator controls and displays. - The DACS is manually controlled through an operator console, which interfaces with the computer through a digital input/output unit. The console consists of pushbutton, thumb wheel, and rotary switches, the functions of which are completely determined by computer software. Using the console, the operator can control programs to calibrate the data acquisition system, acquire and record data, control temperature, play back previously recorded data, and display acquired data.

Two display devices are used during laboratory heating tests: a television-compatible alphanumeric display and a computer graphics terminal. The television system is used for a real time engineering units display of acquired data. Temperature control system performance is displayed on the computer graphics screen. Post-simulation-reduced data are output on a line printer. Reference 4 describes the use of the displays for heating tests of the YF-12A airplane.

Data acquisition and control system programs. - The DACS equipment allows great flexibility of test configuration. Test parameters, such as the number and types of data channels, the data sampling and recording rates, and the number of temperature control channels, are dictated by test objectives. Consequently, DACS programs were written to incorporate the same degree of flexibility as provided by the equipment.

To simplify programming, as well as debugging and program modification, a modular approach was taken. That is, DACS operation was broken down into functions, such as data acquisition, temperature control, and display. A separate program was written for each function. The execution of the programs was coordinated by a real time executive system.

Real time executive system: All the programs that operate the DACS equipment are under the supervision of a real time multiprogramming executive system. The executive system allows the orderly scheduling, initiation, interaction, input/output, and termination of DACS programs required for acquisition and control. Background operations, such as assembling, debugging, and executing programs not directly associated with real time functions, are also controlled by the executive system.

Executive system components, as well as the programs that operate under the control of the executive system, are stored on a fixed head disk file. They can be loaded into the computer and executed when needed.

Setup program: The setup program is used to input test specifications via the system's card reader and convert them to suitable form for the other system programs. The number and sequence of data channels, the channel input sensitivities, the types of transducers connected to the data channel inputs, the correlation between data and control channels, and the display channel assignments are established by the setup program. For transducers with individual sensitivities, the setup program accepts values for the transducer engineering unit outputs that correspond to initial test conditions and transducer standardization signals. The setup parameters are then converted to specific table formats and stored on the fixed head disk file for use by other system programs.

Calibration program: The calibration program provides zero data to cancel channel input offsets, calibrates channel input sensitivity, provides transducer standardizations (such as strain gage shunt calibrations), and checks the operation of the transducer/data channel combination. The program applies known inputs or changes in inputs by activating calibration relays in the data acquisition sites. The data channels are then sampled to obtain channel calibration data. All calibration data are stored on the fixed head disk for later transfer to magnetic output tape, as well as for use by other DACS software programs.

Channel offsets are determined by substituting 0 millivolt for the normal transducer signal for all channel input sensitivities. The resulting digital data are then negated to be used by the offset adder in the acquisition site interface. Voltage substitution calibration data are also used to obtain channel input sensitivities and to verify the linearity of the analog-to-digital conversion processes.

For appropriate transducers, the calibration program uses transducer standardization data and engineering unit conversion factors to calculate constants for real time display purposes. The constants calculated are $\frac{\Delta EU}{\Delta C}$ and $EU_0 = EU_I - \frac{\Delta EU}{\Delta C} C_I$. The real time engineering unit display calculation then reduces to $EU = \frac{\Delta EU}{\Delta C} C + EU_0$. Display constants are stored on the fixed head disk for use by the display program.

The calibration program performs several checks on the operation of the transducer/data channel combination. Voltage substitution calibration data are compared with the expected values to determine whether channel zero adjustments are within reasonable limits and whether channel gain adjustments are within 0.2 percent of the nominal values. Amplifier input short and transducer excitation defeat calibrations, in conjunction with 0-millivolt substitution calibrations, are used to detect data acquisition channel noise. In addition, the operation of the open control thermocouple protection circuit is checked. Finally, the calibrations for those channels that should have valid transducer calibrations are checked.

Acquisition program: The acquisition program uses scan sequence and gain information provided by the setup program and zero offset data supplied by the calibration program to acquire corrected transducer data from the acquisition channels, block the data into records, and record scan data on magnetic tape. Data scans are double buffered so that scanning can occur at the same time as data recording, data display, and temperature control. The acquisition program uses operator console inputs to initiate and terminate data recording on magnetic tape. When recording is initiated, calibration data are copied onto magnetic tape from the system disk file. Then test data scans are recorded until the operator terminates data sampling, data recording, or both.

Data sampling and recording rates are also controlled by the acquisition program through operator console inputs. Data were sampled at 10 scans per second and recorded once per second for the YF-12A heating tests (ref. 4).

If an off-scale interrupt is sent from the acquisition interface, the program determines which channel caused the interrupt, decreases the channel input sensitivity, and obtains a zero offset correction for that channel at the new sensitivity from the fixed head disk. Thus, data channels can be sampled at sensitivities high enough to insure adequate resolution while maintaining sufficient range to cope with unexpected transducer outputs.

The loss of multiplexer synchronism is also indicated to the acquisition program by a priority interrupt from the acquisition interface. The program responds to this condition by halting the acquisition process, invalidating the affected acquisition scan, and re-initializing acquisition to restore proper acquisition channel identification.

Temperature control program: The temperature control program regulates the power supplied to each control zone heater to cause feedback thermocouple data supplied by the acquisition program to follow setpoint data from a magnetic tape (ref. 4).

The control tape contains time histories of desired feedback and monitors thermocouple data converted to data acquisition system counts. Each record on the control tape consists of elapsed time simulation data as well as the desired temperatures for that time point. The control program reads these records as required and linearly interpolates between time points to arrive at desired temperatures for actual elapsed simulation times. Interpolation reduces the number of control tape records to those required to adequately describe the desired temperature profiles, thereby minimizing computer input/output overhead.

Another advantage of the interpolation scheme is the simplification of simulation startup. Generally, the temperatures desired at the beginning of simulation are not the same as ambient feedback temperatures. Therefore, it is necessary to raise (or lower) control/feedback temperatures to profile starting values without causing undesirable temperature gradients in the test

specimen.[1] The control program accomplished this by linearly raising each feedback temperature from ambient to its profile starting value. The duration of the temperature rise is calculated so that the maximum temperature rise rate for any control zone is 0.19 K per second (0.33° F per second), an arbitrary value low enough to prevent serious temperature gradients in most aircraft structures. Desired control temperatures are calculated by interpolating the measured ambient temperatures and the initial desired temperatures for the duration of the temperature rise.

Because of the magnitude of the YF-12A heating test, it was necessary to develop a simple, reliable method of temperature control. To eliminate the manual tuning associated with conventional analog controllers, and to avoid the test iterations required by the technique used in the Concorde radiant heating tests (ref. 5), an adaptive control scheme was used. The control of each heating zone was based on a model of the heating process for that zone. This model was adjusted on the basis of actual zone performance.

The following equation was the model used in the heating of the YF-12A airplane:

$$P_n = K_1 \frac{T_n - T_{n-1}}{t_n - t_{n-1}} + K_2 \left(T_n - T_0 \right) \qquad (1)$$

where P_n represents the power applied to the zone by the radiant heaters and the first and second terms on the right side of the equation represent energy storage and loss rates for the heated zone. Note that, in contrast to conventional closed loop control methods, the equation does not use control error. Thus, the control program does not calculate control errors.

The control program used the control equation (eq. (1)) to command the application of power to each zone heater for discrete periods of time. The power level to be applied was calculated at the beginning of each 1-second period by using the current feedback data value, the temperature data desired at the end of the control period, the current values of K_1 and K_2, and the initial value of feedback thermocouple output. Thus, the control equation became:

$$P_{n+1} = K_1 \frac{\hat{T}_{n+1} - \hat{T}_n}{t_{n+1} - t_n} + K_2 \left(\hat{T}_{n+1} - T_0 \right)$$

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[1]For the YF-12A heating tests, aircraft skin temperatures for the portion of flight chosen for simulation were above laboratory ambient temperatures. Otherwise, it would have been necessary to precool the airplane, as per the simulation discussed in reference 3.

Every 8 seconds, the parameters K_1 and K_2 were simultaneously calculated by submitting actual power levels and feedback temperature data for the two different times t_n and t_{n-8} into equation (1).

It was impossible for the simultaneous equations to be linearly dependent, or so nearly dependent that the calculation of K_1 and K_2 was adversely affected by the data system noise. In addition, the rates of temperature change in these equations were particularly susceptible to errors due to noisy feedback data. Therefore, it was necessary to verify that calculated rates of temperature change were valid, that the denominator used in the simultaneous solution

$$(T_n - T_0)\left(\frac{T_{n-8} - T_{n-9}}{t_{n-8} - t_{n-9}}\right) - (T_{n-8} - T_0)\left(\frac{T_n - T_{n-1}}{t_n - t_{n-1}}\right)$$

was not zero, and that the calculated values of K_1 and K_2 were reasonable. If the control parameter calculation did not meet these criteria, the new values of K_1 and K_2 were discarded and the old values were retained.

Equation (1) is, admittedly, a crude approximation of the actual heating process. The rate at which energy is stored in the heated zone depends, for example, not only on the rate of change of feedback thermocouple temperature, but also on the temperature distribution throughout the zone. Nevertheless, acceptable control is possible, since the parameters K_1 and K_2 are assumed to be functions of unmeasured control variables, and are adjusted often enough to account for changes in those variables.

The control program, in addition to being initiated or terminated by operator console switch inputs, can also be placed in a hold condition from the console. Simulation profile elapsed time and desired temperatures remain constant while control is maintained for the duration of the hold condition.

Display program: The display program utilizes data provided by the setup, calibration, acquisition, and control programs. These data are used to generate a real time alphanumeric data display and a control error display for operator information. The display program also monitors temperature control errors and terminates the simulation if errors exceed predetermined values.

The alphanumeric data display is capable of displaying up to 10 data acquisition channels in engineering units, raw counts, or counts normalized to calibrate. Channels to be displayed are assigned through the setup program or through the operator console.

The alphanumeric display also provides test personnel with information related to acquisition and control conditions. Acquisition parameters, such as run identification, elapsed time, scan rate, and scan recording rate, are displayed. Control profile elapsed time, hold elapsed time, and assigned maximum allowable power level command are also provided as operator information.

Monitoring the performance of the large number of control channels, as in the YF-12A heating simulation, makes it necessary to have a display that provides enough information to check the operation of the control system without overwhelming the observer with irrelevant data. To meet this requirement, the display program calculates and displays control errors in analog form for all control channels, and identifies only those channels with significant errors. This provides a concise, straightforward display.

Figure 12 shows the control error display during the laboratory test of a YF-12A airplane duplicating Mach 3 heating simulation. Each control channel is represented by a dot with a vertical displacement from a zero error line that is proportional to control error. The two horizontal lines at the center of the screen divide the display into two groups of error channels, and the vertical partitions with two-letter codes identify the locations on the airplane of groups of control thermocouples. Each division on the left vertical axis represents a 5.6 K (10° F) error. The horizontal dashed lines in figure 12 represent error alarm thresholds. Any control channel with a positive or negative error greater than a predetermined value is listed on the left margin of the display.

Analog Electrohydraulic and Thermal Load Control Systems

Figure 13 is a block diagram of the hydraulic and thermal load control systems. These systems have the capability of loading and heating test specimens simultaneously by following programs of load and temperature. The hydraulic and thermal load control systems are programmed by the same type of function generator and by similar controllers. Both the function generators and the hydraulic and thermal load controllers described in this section are analog devices that are independent of the DACS.

The function generator, as used for loading, is a device that enables the user to program the load applied to a specimen as a function of time. This is accomplished by plotting the desired load time history on a sheet of metallic graph paper, attaching the graph to a drum, and inserting the drum into the function generator. After the system is energized, the drum turns, and a servo-controlled probe follows the curve, driving an actuator as required to maintain the load indicated by the graph. The actuator loads the test specimen through a load cell which feeds a signal back to the load controller, thus completing the servo loop. In a similar way, temperature is programmed by the function generator, which drives a temperature controller and varies the voltage level to the lamps as required to maintain the temperature indicated by the graph. A thermocouple at the control point feeds a signal back to the temperature controller to complete the servo loop.

The function generators used are adjustable to provide time bases from 1.69 centimeters per second (2.40 inches per hour) to 0.00265 centimeter per second (3.75 inches per hour) with an accuracy and repeatability within 1 percent of elapsed time. The performance characteristics of the function generators are as follows:

- Maximum probe-following rate is 17.8 centimeters per second (7 inches per second).

- Static positional accuracy and repeatability of the probe is 0.1 percent of full scale.

- Dynamic positional accuracy of the probe is 1.0 percent at maximum probe-following rate.

- Set point or manual operation can be performed.

Electrohydraulic loading system (analog). - The hydraulic loading system consists of 28 channels of closed loop load or position control with function generators of the type described in the preceding section. Ninety-eight actuators are available for use with this system. The configuration and physical characteristics of the hydraulic actuators are presented in table I. Hydraulic power is supplied to the actuators through a flexible high-pressure hose which connects the actuator to hydraulic pressure and return lines located in the floor trenches.

The hydraulic loading system has fail-safe provisions, as shown in figure 14. A first precaution is to limit the hydraulic pressure to permit the actuator to apply only the required load. A second protective device is a limit switch, which can cause one of two preselected events: indicate only or lock and dump. For a lock and dump situation, the lock valves close (preventing flow into the actuator) and the dump valves open (releasing pressure from both sides of the actuator), relieving the applied load. A third device is an error-detection system which senses the error between feedback and command. If the error exceeds a predetermined amount, the system will cause one of the two preselected events mentioned previously: indicate only or lock and dump. A fourth protection is a load limit detection system which senses a preselected load limit and causes the system to indicate or lock and dump. Hydraulic pressure regulators are also available for each channel.

Thermal loading system (analog). - The available programmed analog heating equipment consists of 24 power control channels plus two portable three-channel units. Significant overloads can be tolerated for short periods of time. Twenty-four channels have a power capability of 100 kilowatts per channel and can be programmed from four function generators as described in a preceding section. Six channels are portable units and can be used wherever 480-volt power is available; three of these channels have a capability of 200 kilowatts per channel. Electrical power is connected to the lamps by flexible cable with high-temperature insulation. The cables to the lamps are routed through floor trenches.

The primary protective or fail-safe capability used with the analog heating equipment is a voltage-limiting system which enables the operator to limit the voltage applied to the heat lamps for each channel control. To use this system effectively it is necessary to know the amount of power needed to achieve the heating rates and temperature levels required by the tests. Once

this information is known, it is necessary to limit the power applied to each channel to avoid exceeding those values.

Heat is normally applied to the specimen through the use of infrared quartz lamps, which are available in various lengths from 12.7 centimeters (5 inches) to 81.3 centimeters (32 inches) (lighted lengths). Reflector arrangements are readily adaptable to individual requirements for heating rates in the range from 0 to 1.13 MW/m^2-sec (100 Btu/ft^2-sec) and temperatures up to 1922 K (3000° F). Typical heating tests are described in references 3 and 4.

Air Operated Hydraulic Loading System

Two portable manually controlled air operated hydraulic loading systems are available for use with the actuators listed in table 1. Figure 15 is a schematic on the operation of these systems. The pressure and flow capabilities are shown in figure 16. These units are open loop manually operated devices and do not have the fail-safe provisions described above except for pressure regulation.

Ground Vibration Test System

The capability of the ground vibration test system may be summarized as follows:

- The four-channel dynamic analysis and test system (DATS) has the ability to determine the modal characteristics of vehicles during ground tests while providing vibration control for shakers utilizing a closed loop digital controller.
- Four-channel shaker capability: two 222-newton (50-pound) shakers and two 667-newton (150-pound) shakers
- Ten channels of accelerometers
- Ten channel display of signal root-mean-square voltage
- Eight-channel strip chart
- Eight oscilloscope channels
- Single-channel frequency sweep oscillator control
- Single-channel frequency counter
- Six-channel tracking filter capability (selectable bandwidths of 1 Hz, 2 Hz, and 5 Hz)
- Single-channel co-quad analyzer

- Nine-channel tape recorder

- Six channels of X-Y plotting capability

- Impulse hammer

Universal Testing Machines

The Facility has three universal testing machines. Two of the machines are closed loop electrohydraulic machines with digital engineering unit displays and an X-Y recorder. Figure 17 is a photograph of these 444,822-newton (100,000-pound) machines. The third machine is a screw-power machine with a mechanical load display. The capacity of each machine is as follows:

Capacity, N (lb)	Type
444,822 (100,000)	Electrohydraulic, closed loop
44,482 (10,000)	Electrohydraulic, closed loop
11,121 (2,500)	Mechanical screw power

Ovens

The Facility has seven ovens (fig. 18) with the capabilities described in table 2. Six of the ovens are of the noncycling type and are manually set to hold a temperature within their temperature range (items 2, 4, and 5 in table 2). One oven (item 3) is a cycling oven which can be cycled from -73° C to 316° C (-100° F to 600° F) utilizing liquid nitrogen.

Communication System

The Flight Loads Research Facility closed circuit television system (CCTS) permits the operator of the analog load control system to view hydraulic jacks and also enables test personnel to monitor tests from the FLRF control room that would otherwise be obstructed from the viewing window.

The current CCTS consists of three transistorized vidicon cameras. Two of the cameras are stationary and have fixed focus lenses. The third camera is equipped with a motorized zoom lens. The motorized camera has a range of focal lengths from 15 millimeters to 170 millimeters, with a focusing range of 12 meters (39 feet) to infinity. A pan and tilt unit enables the camera and zoom lens assembly to be positioned by remote control from the FLRF control room. The pan portion permits the camera assembly to turn horizontally through 350°, with easy adjustments to limit movements to smaller angles. The tilt portion permits tilt movements of ±90° from the level position. The camera/tilt, pan assembly is mounted on a stand that allows a vertical height movement

of up to 3.4 meters (11 feet). The camera and stand assembly can be rolled anywhere in the hangar test area. Signals from the camera are routed to the FLRF control room by cables in the hangar floor trenches.

Television monitors receive signals from the camera as well as from the computer control system. These signals can be monitored on six black and white television monitors: four with 33-centimeter (13-inch) screens and four with 20.3-centimeter (8-inch) screens. The four monitors are located in a monitor console rack located in the FLRF control room. One of the 33-centimeter (13-inch) monitors is located in the FLRF control room, and the remaining 33-centimeter (13-inch) monitors are located in the hangar test area. The CCTS has the capability of splitting, fading, and superimposing the incoming video signals from the cameras or from the computer/camera combination.

Moment of Inertia Equipment

The moment of inertia equipment available for use in the FLRF consists of the following:

- Calibrated springs (table 3)
- Three-axis rate gyro package (40 deg/sec)
- Transit and level
- Strip chart recorder

Figure 19 shows a typical moment of inertia test being conducted on the PA-30 aircraft.

Shop Equipment

The major items of shop equipment are summarized in the table below. The numerically controlled punch machine can be utilized to punch holes in reflector materials for lamp support and reflector supports. One drill press is a large radial arm device capable of drilling large holes in structural steel (fig. 20).

Type of equipment	Quantity
Numerically controlled punch machine	1
Lathe	2
Milling machine	1
Drill press	3
Lapping machine	1
Welders	3
Belt sanders	2
Bandsaws	2

Liquid Nitrogen

Liquid nitrogen (LN_2) is utilized in the FLRF to cool test structures below ambient conditions. Two storage tanks are available; the smaller one is shown in figure 9. The tanks have the following capacities:

Tank	Capacity, l (gal)	Flow rate, l/sec (gal/min)	Pressure, kN/m^2 (lb/in^2)
1	3,785 (1,000)	0 to 1.89 (0 to 30)	0 to 1724 (0 to 250)
2	15,140 (4,000)	0 to 25.23 (0 to 400)	0 to 379 (0 to 55)

Structural Erector Set

The Facility has an erector set made up of steel and aluminum channels of various sizes including fittings. The erector set can be used to construct structural fixtures to suit various test configurations. Table 4 is a listing of the available sizes of channels.

INSTRUMENTATION

Most of the transducers available for use in the facility are strain gage, thermocouple, load cell, and position transducers.

Strain Gages

A strain gage laboratory within the Facility provides the capability for installing and testing strain gages under environmental conditions of heat and load. Various types of strain gages, including those requiring welded and flame-spray attachments, can be installed. Thermocouples can also be installed in the strain gage laboratory. Typically the thermocouples used are spot welded Chromel-Alumel.

Load Cells

The configuration and physical characteristics of the load cells available in the facility are presented in table 5.

Aircraft Weighing Kits

Six standard self-contained aircraft weighing kits with the capacities shown in table 6 are available.

Displacement Transducers

One hundred and thirty-two potentiometric displacement transducers with the specifications shown in table 7 are available.

Twenty-four dial-gage displacement-measuring devices are also available, with ranges varying from 0.096 centimeter (3/8 inch) to 10.16 centimeters (4 inches).

CONCLUDING REMARKS

The NASA Dryden Flight Loads Research Facility provides the capability for both loading and heating flight structures under controlled conditions and simultaneously acquiring data from a large number of sensors. It is particularly well suited for installing and calibrating strain gage installations for in-flight structural loads measurements and for the application of structural proof-test loads in support of flight safety when the simulation of aerodynamic heating is required. The facility has the capability for performing ground vibration tests and moment of inertia tests on aircraft and aircraft components.

Dryden Flight Research Facility
Ames Research Center
National Aeronautics and Space Administration
Edwards, California 93523
September 1, 1981

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1. Sefic, Walter J.; and Anderson, Karl F.: NASA High Temperature Loads Calibration Laboratory. NASA TM X-1868, 1969.

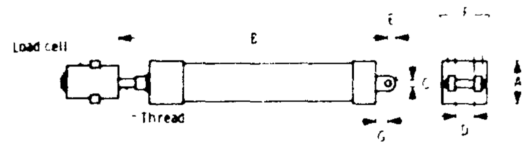
2. Wilson, Earl J.: Use of Strain Gages for Measurements of Flight Loads in a High-Temperature Environment. Paper 68-555, Instr. Soc. Am. Oct. 1968.

3. Fields, Roger A.; and Vano, Andrew: Evaluation of an Infrared Heating Simulation of a Mach 4.63 Flight on an X-15 Horizontal Stabilizer. NASA TN D-5403, 1969.

4. NASA YF-12 Flight Loads Program. NASA TM X-3061, 1974.

5. Examples of the Use of a Computer in Real Time: Carrying Out Structural Tests of the Concord Aircraft. NASA TT F-11,999, 1968.

TABLE 1 - HYDRAULIC ACTUATOR PHYSICAL CHARACTERISTICS



	Maximum load at full stroke		Stroke, cm (in.)	Quantity	Thread type	Bore, cm (in)	Rod diameter, cm² (in²)	Piston area	
	Tension, N (lb)	Compression, N (lb)						Tension, cm² (in²)	Compression, cm² (in²)
A	15,568 (3,500)	8,006 (1,800)	15 2 (6)	2	1/2-20 NF	3 81 (1 50)	1 90 (0 750)	3 36 (1 326)	4 48 (1 767)
B	17,792 (4,000)	8,006 (1,800)	15 2 (6)	22	1/2-20 NF	3 81 (1 50)	1.58 (0 625)	3 71 (1 460)	4 48 (1 767)
C	17,792 (4,000)	1,779 (400)	30.4 (12)	2	1/2-10 NF	3 81 (1 50)	1 58 (0 625)	3.71 (1 460)	4 48 (1 767)
	17,792 (4,000)	1,779 (400)	30.4 (12)	4	1/2-10 NF	3 81 (1.50)	1.58 (0 625)	3 71 (1 460)	4 48 (1 767)
D	20,016 (4,500)	12,899 (2,900)	60 9 (24)	4	1-14 NF	5 08 (2 00)	3.49 (1 375)	4.21 (1 660)	7 98 (3 142)
E	13,304 (3,000)	20,016 (4,500)	45 7 (18)	4	1-14 NF	6 35 (2 50)	3.52 (1 386)	8 60 (3.400)	12 46 (4 909)
F	31,137 (7,000)	44,482 (10,000)	60 9 (24)	6	1-14 NF	6 35 (2 50)	4 44 (1 750)	6 35 (2 500)	12 46 (4 909)
G	66,723 (15,000)	71,171 (16,000)	60 9 (24)	4	1-14 NF	8 25 (3 25)	5 08 (2 000)	13 10 (5 160)	21 06 (8 292)
H	120,101 (27,000)	71,171 (16,000)	60 9 (24)	4	1 1/2-12 NF	10 16 (4 00)	5.08 (2 000)	23 [illegible]0 (9 420)	31 91 (12 566)
	120,101 (27,000)	71,171 (16,000)	60 9 (24)	2	1 1/2-12 NF	10 16 (4 00)	5 08 (2 000)	23 90 (9 420)	31 91 (12 566)
J	88,964 (20,000)	160,135 (36,000)	60 9 (24)	4	1 1/2-12 NF	10 16 (4 00)	6 35 (2 500)	19 40 (7 657)	31 91 (12 566)
K	266,893 (60,000)	355,857 (80,000)	45 7 (18)	2	2-12 N	15 24 (6 00)	7.62 (3 000)	23 80 (21 205)	71 80 (28 274)
L	31,137 (7,000)	80,067 (18,000)	45 7 (18)	9	1-14 NF	6 35 (2 50)	4 44 (1 750)	6 35 (2 500)	12 46 (4 909)
M	53,378 (12,000)	17,792 (4,000)	30 4 (12)	1	1-14 NF	6 35 (2 50)	2.54 (1 000)	10 47 (4 124)	12 46 (4 909)
N	35,585 (8,000)	35,585 (8,000)	10.1 (4)	1	1-14 NF	6 35 (2 50)	2 54 (1.000)	10 47 (4 124)	10 47 (4 124)
O	52,278 (12,000)	64,499 (14,500)	10 1 (4)	14	1-14 NF	6 35 (2 50)	2 54 (1 000)	10 47 (4 124)	12 46 (4 909)
P	88,964 (20,000)	106,757 (24,000)	15 2 (6)	10	1-14 NF	7 62 (3 00)	3 49 (1.375)	17 29 (6 811)	21 07 (8 296)
Q	31,137 (7,000)	41,813 (9,400)	15 2 (6)	6	1-14 NF	5 08 (2 00)	2.54 (1 000)	5 98 (2 356)	7 98 (3 142)

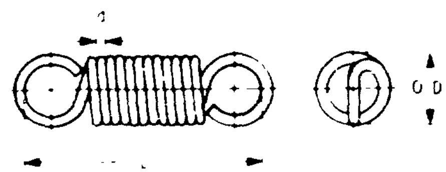
Table 1. - Concluded

	Dimension							Maximum hydraulic pressure,
	a, cm (in.)	b, cm (in.)	c, cm (in.)	d, cm (in.)	e, cm (in.)	f, cm (in.)	g, cm (in.)	kN/m^2 (lb/in^2)
A	6.35 (2.5)	33.02 (13.000)	1.27 (0.50)	------------	-----------	-----------	1.900 (0.75)	20,684 (3000)
B	6.35 (2.5)	31.75 (12.500)	1.27 (0.50)	1.900 (0.75)	1.27 (0.50)	1.27 (0.50)	1.900 (0.75)	20,684 (3000)
C	6.35 (2.5)	47.30 (18.625)	1.27 (0.50)	1.900 (0.75)	1.27 (0.50)	1.27 (0.50)	1.900 (0.75)	20,684 (3000)
	6.35 (2.5)	50.16 (19.750)	1.27 (0.50)	1.900 (0.75)	1.27 (0.50)	1.27 (0.50)	1.900 (0.75)	20,684 (3000)
D	7.62 (3.0)	101.60 (40.000)	1.90 (0.75)	3.175 (1.25)	1.90 (0.75)	1.60 (0.63)	3.175 (1.25)	20,684 (3000)
E	8.89 (3.5)	63.50 (25.000)	1.27 (0.50)	3.175 (1.25)	1.90 (0.75)	1.60 (0.63)	3.175 (1.25)	6,894 (1000)
F	8.89 (3.5)	101.90 (40.125)	1.90 (0.75)	3.175 (1.25)	1.90 (0.75)	1.60 (0.63)	3.175 (1.25)	20,684 (3000)
G	11.43 (4.5)	105.41 (41.500)	2.54 (1.00)	3.810 (1.50)	2.54 (1.00)	1.90 (0.75)	3.810 (1.50)	20,684 (3000)
H	12.70 (5.0)	102.87 (40.500)	3.50 (1.38)	5.080 (2.00)	3.50 (1.38)	2.54 (1.00)	5.400 (2.13)	20,684 (3000)
	12.70 (5.0)	104.77 (41.250)	3.50 (1.38)	5.080 (2.00)	3.50 (1.38)	2.54 (1.00)	5.400 (2.13)	20,684 (3000)
J	12.70 (5.0)	91.44 (36.000)	3.50 (1.38)	5.080 (2.00)	3.50 (1.38)	2.54 (1.00)	5.400 (2.13)	20,684 (3000)
K	19.05 (7.5)	79.37 (31.250)	5.08 (2.00)	6.350 (2.50)	5.08 (2.00)	3.18 (1.25)	6.350 (2.50)	20,684 (3000)
L	8.89 (3.5)	69.21 (27.250)	1.90 (0.75)	3.175 (1.25)	1.90 (0.75)	1.60 (0.63)	3.175 (1.25)	20,684 (3000)
M	8.89 (3.5)	50.80 (20.000)	1.90 (0.75)	3.175 (1.25)	1.90 (0.75)	1.60 (0.63)	3.175 (1.25)	20,684 (3000)
N	8.89 (3.5)	45.72 (18.000)	-----------	------------	-----------	-----------	------------	13,789 (2000)
O	8.89 (3.5)	28.89 (11.375)	1.90 (0.75)	3.175 (1.25)	1.90 (0.75)	1.60 (0.63)	3.175 (1.25)	20,684 (3000)
P	11.43 (4.5)	11.74 (4.625)	1.54 (1.00)	3.810 (1.50)	2.54 (1.00)	1.90 (0.75)	3.810 (1.50)	20,684 (3000)
Q	7.62 (3.0)	33.00 (13.000)	1.90 (0.75)	3.175 (1.25)	2.54 (1.00)	3.81 (1.50)	3.175 (1.25)	20,684 (3000)

TABLE 2. - OVEN CONFIGURATIL

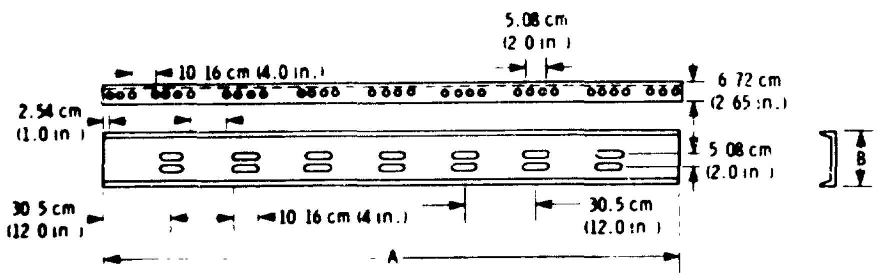
Item	Temperature range, K (°F)	Quantity	Inside dimensions, width × depth × height, cm (in.)	Type
1	Ambient to 978 (1300)	3	97 × 51 × 64 (38 × 20 × 25)	Mechanical convection
2	Ambient to 672 (750)	1	91 × 122 × 152 (36 × 48 × 60)	Mechanical convection
3	200 to 589 (-100 to 600)	1	122 × 122 × 122 (48 × 48 × 48)	Mechanical convection with liquid nitrogen cooling
4	Ambient to 617 (650)	1	51 × 46 × 51 (20 × 18 × 20)	Mechanical convection
5	Ambient to 1367 (2000)	1	31 × 25 × 71 (12 × 10 × 28)	Radiant heat

TABLE 3 - INERTIA EQUIPMENT SPRING CHARACTERISTICS



Spring	Spring constant, N/m (lb/ft)	L, cm (in.)	O.D., cm (in.)	d, cm (in.)	Quantity
A	1,751 (120)	15.24 (6.00)	2.92 (1.15)	0.318 (0.125)	4
B	4,232 (290)	22.23 (8.75)	2.95 (1.16)	0.414 (0.163)	4
C	7,442 (510)	21.59 (8.50)	3.81 (1.50)	0.533 (0.210)	4
D	14,448 (990)	28.58 (11.25)	3.81 (1.50)	0.635 (0.250)	4
E	11,237 (770)	43.18 (17.00)	4.52 (1.78)	0.978 (0.385)	4
F	7,442 (510)	33.02 (13.00)	4.14 (1.63)	0.610 (0.240)	4
G	3,794 (260)	22.23 (8.75)	3.81 (1.50)	0.483 (0.190)	4
H	1,897 (130)	17.78 (7.00)	3.81 (1.50)	0.394 (0.155)	3

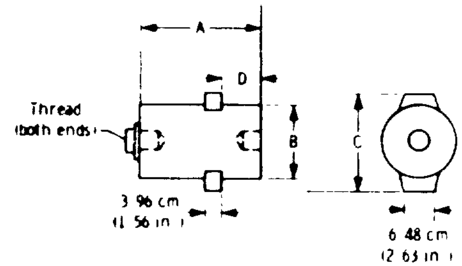
TABLE 4. - ERECTOR SET CONFIGURATION



All holes and slots 1.47 cm (37/64 in.). Drawing not to scale.

Item with dimensions—		Material	Designation	Quantity
A, m (ft)	B, cm (in.)			
0.76 (2.5)	30.5 (12)	Steel	12U20.7	4
1.22 (4.0)	15.2 (6)	Steel	6U13	4
1.52 (5.0)	15.2 (6)	Steel	6U13	4
1.83 (6.0)	15.2 (6)	Steel	6U13	4
1.22 (4.0)	25.4 (10)	Steel	10U20	24
2.44 (8.0)	22.9 (9)	Steel	9U20	12
3.05 (10.0)	22.9 (9)	Steel	9U20	20
3.66 (12.0)	22.9 (9)	Steel	9U20	14
3.96 (13.0)	22.9 (9)	Steel	9U20	6
4.27 (14.0)	22.9 (9)	Steel	9U20	4
4.88 (16.0)	22.9 (9)	Steel	9U20	4
1.07 (3.5)	22.9 (9)	Aluminum	6U4.48	2
1.22 (4.0)	22.9 (9)	Aluminum	9U6.91	4
2.44 (8.0)	22.9 (9)	Aluminum	9U6.91	4
3.05 (10.0)	22.9 (9)	Aluminum	9U6.91	4
3.66 ([illegible])	22.9 (9)	Aluminum	9U6.91	4
4.57 (15.0)	22.9 (9)	Aluminum	9U6.91	8
4.88 (16.0)	22.9 (9)	Aluminum	9U6.91	4

TABLE 5 - LOAD CELL CONFIGURATION AND PHYSICAL CHARACTERISTICS



Capacity, N (lb)	Dimension				Thread	Quantity	Accuracy, percent of full scale
	A, cm (in.)	B, cm (in.)	C, cm (in.)	D, cm (in.)			
2,224 (500)	11.58 (4.56)	8 89 (3.50)	14.30 (5.63)	3.18 (1.25)	1/2-20 NF	1	0 25
8,896 (2,000)	11.58 (4.56)	8.89 (3.50)	14.30 (5.63)	3.18 (1.25)	1/2-20 NF	8	0.25
22,241 (5,000)	15.09 (5 94)	8.89 (3.50)	14.30 (5.63)	4 60 (1.81)	1-14 NF	4	0 10
22,241 (5,000)	15 09 (5 94)	8 89 (3 50)	14.30 (5.63)	4.60 (1.81)	1-14 NF	8	0 25
44,482 (10,000)	15.09 (5.94)	8.89 (3 50)	14.30 (5 63)	4 60 (1 81)	1-14 NF	4	0 10
44,482 (10,000)	15.09 (5 94)	8.89 (3 50)	14 30 (5 63)	4 60 (1 81)	1-14 NF	7	0 25
88,964 (20,000)	21 59 (8.50)	12.70 (5 00)	17.63 (6.94)	7.14 (2 81)	1 1/2-12 NF	4	0 10
88,964 (20,000)	21 59 (8.50)	12.70 (5.00)	17.63 (6 94)	7 14 (2 81)	1 1/2-12 NF	6	0 25
222,410 (50,000)	29.06 (11.44)	15 88 (6 25)	24.0? (9.46)	14 53 (5 72)	2-12 NF	2	0 10

TABLE 6 - AIRCRAFT WEIGHING KIT CAPACITIES

Capacity per cell, N (lb)	Number of cells	Quantity	Accuracy
44,482 (10,000)	3	3	±0.1 percent of reading or ±8.9 N (±2 lb)
111,205 (25,000)	4	2	±0.1 percent of reading or ±22.2 N (±5 lb)
222,411 (50,000)	3	1	±0.1 percent of reading or ±88.90 N (±20 lb)

TABLE 7. - POTENTIOMETRIC DISPLACEMENT TRANSDUCERS

Range, cm (in.)	Resolution, cm (in.)	Quantity
0 to 2.54 (0 to 1)	±0.008 (±0.003)	40
0 to 7.62 (0 to 3)	±0.018 (±0.007)	50
0 to 15.24 (0 to 6)	±0.025 (±0.010)	20
0 to 30.48 (0 to 12[a])	±0.051 (±0.020)	10
0 to 45.72 (0 to 18)	±0.081 (±0.032)	6
0 to 60.96 (0 to 24)	±0.107 (±0.042)	6

[a]This transducer has a separable cable which permits the cable to release without damage to the component parts when its range is exceeded.

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Figure 1. Front view of NASA Dryden Flight Loads Research Facility.

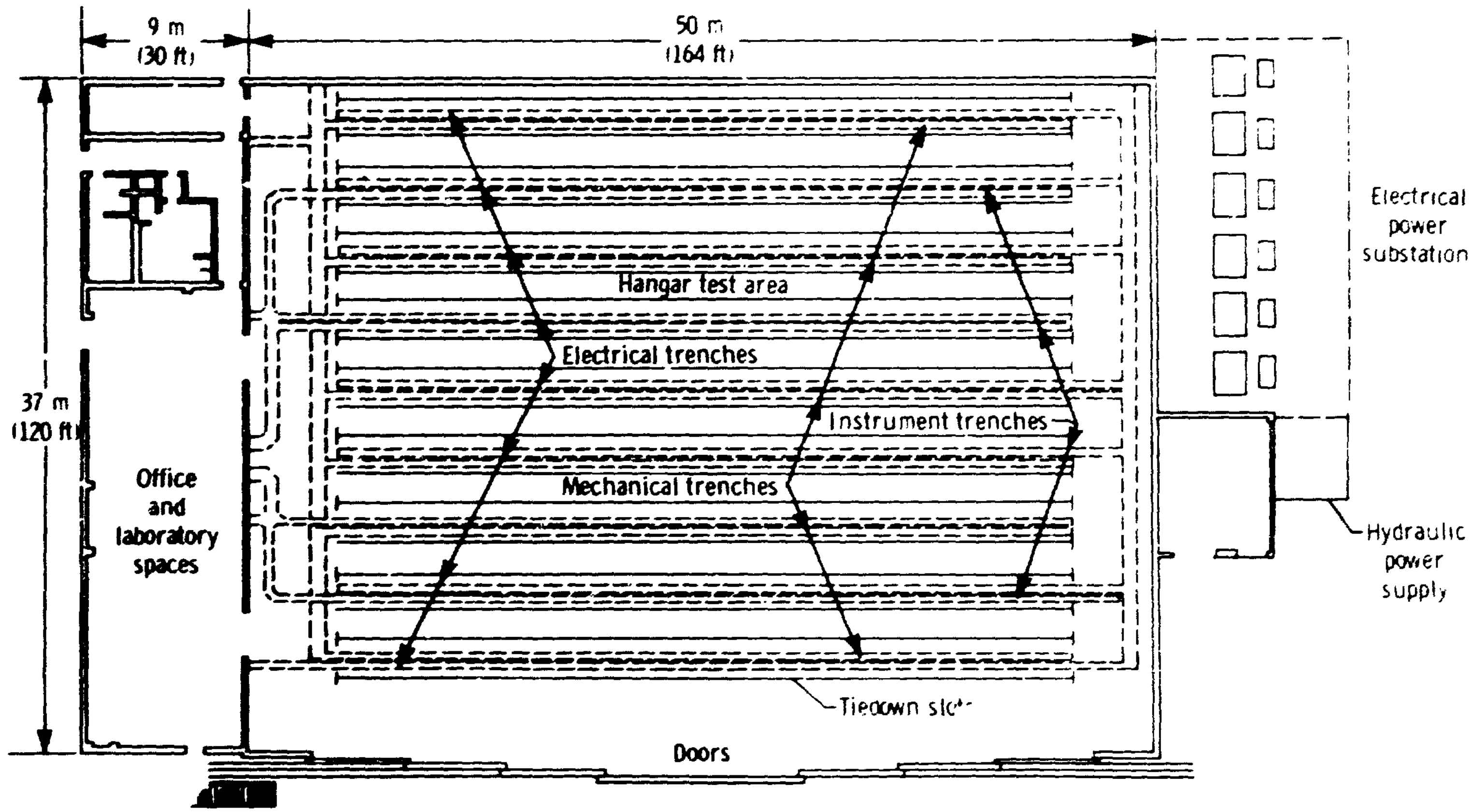

Figure 2. Building layout of NASA Dryden Flight Loads Research Facility.

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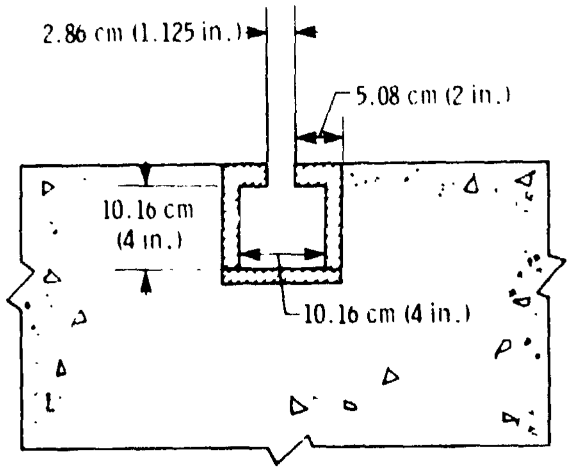

Figure 3. Cross section of typical tiedown slot.

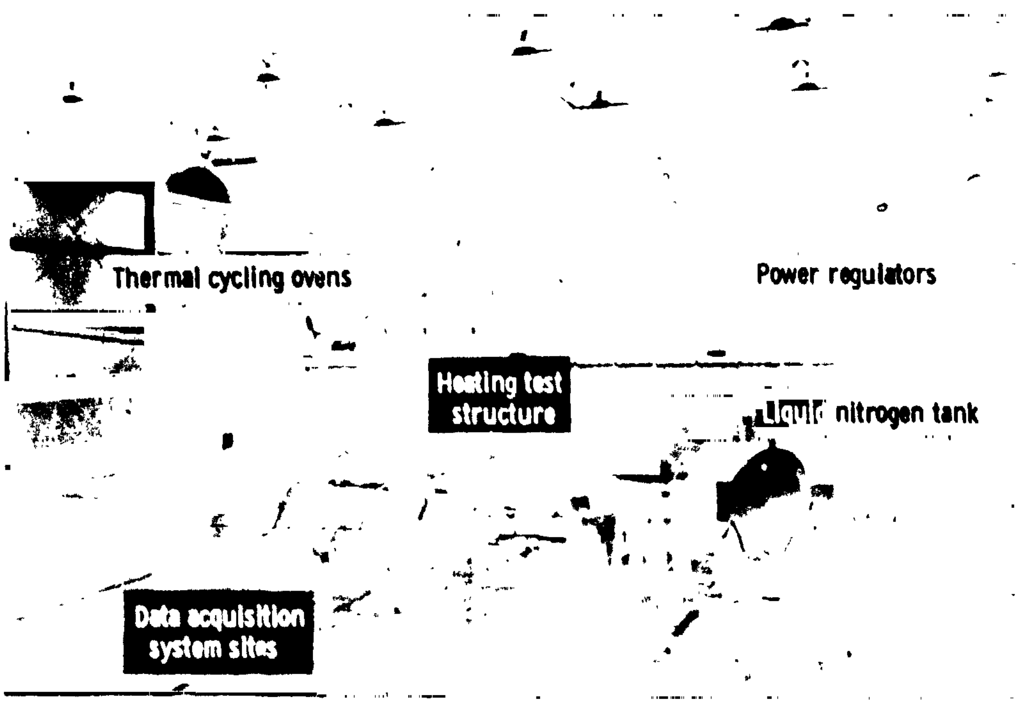

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Figure 4. Interior view of the hangar test area of the NASA Dryden Flight Loads Research Facility.

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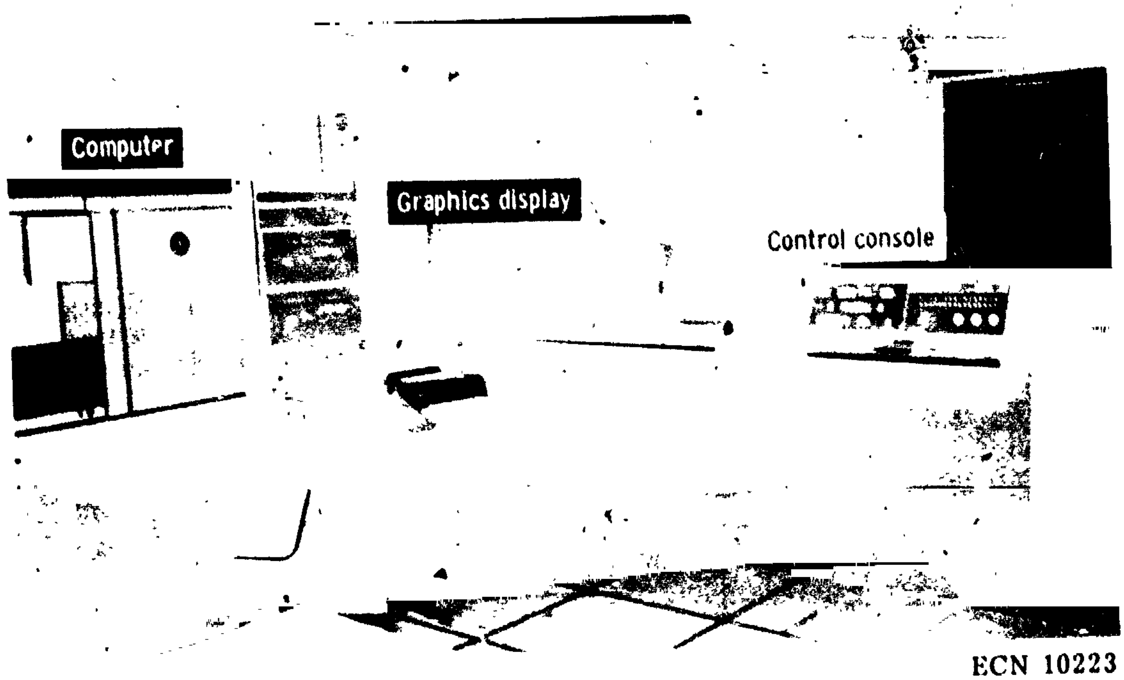

Figure 5. NASA Dryden Flight Loads Research Facility Control Room.

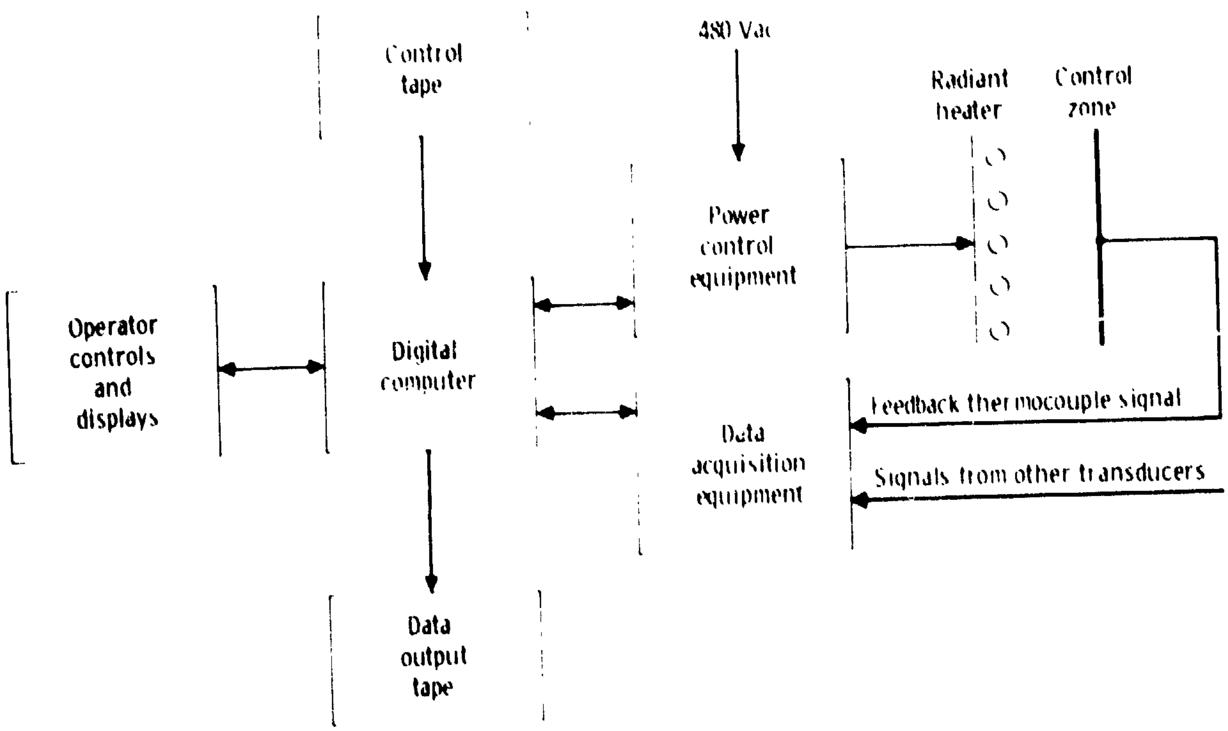

Figure 6. Data acquisition and control system block diagram.

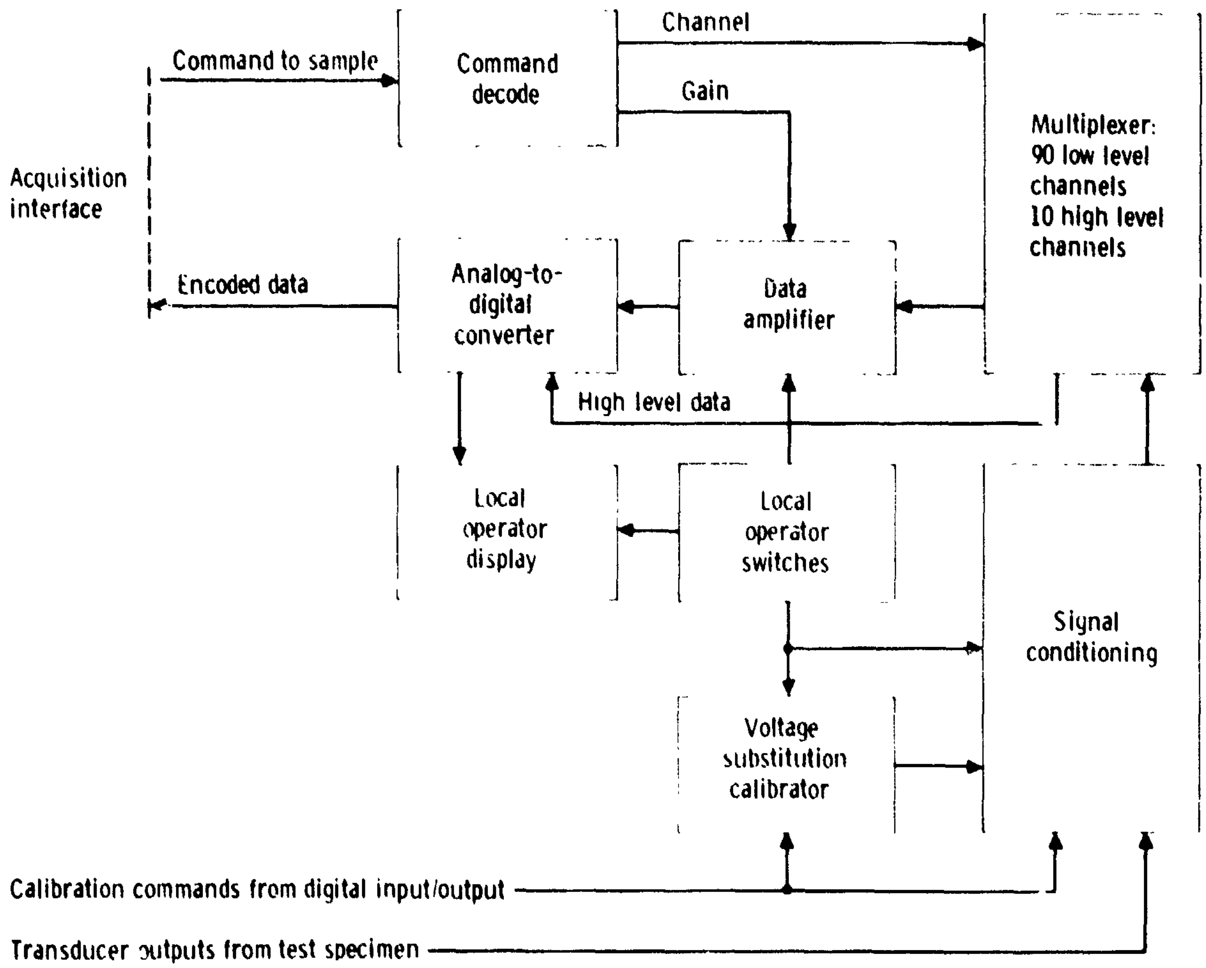

Figure 7. Acquisition site block diagram.

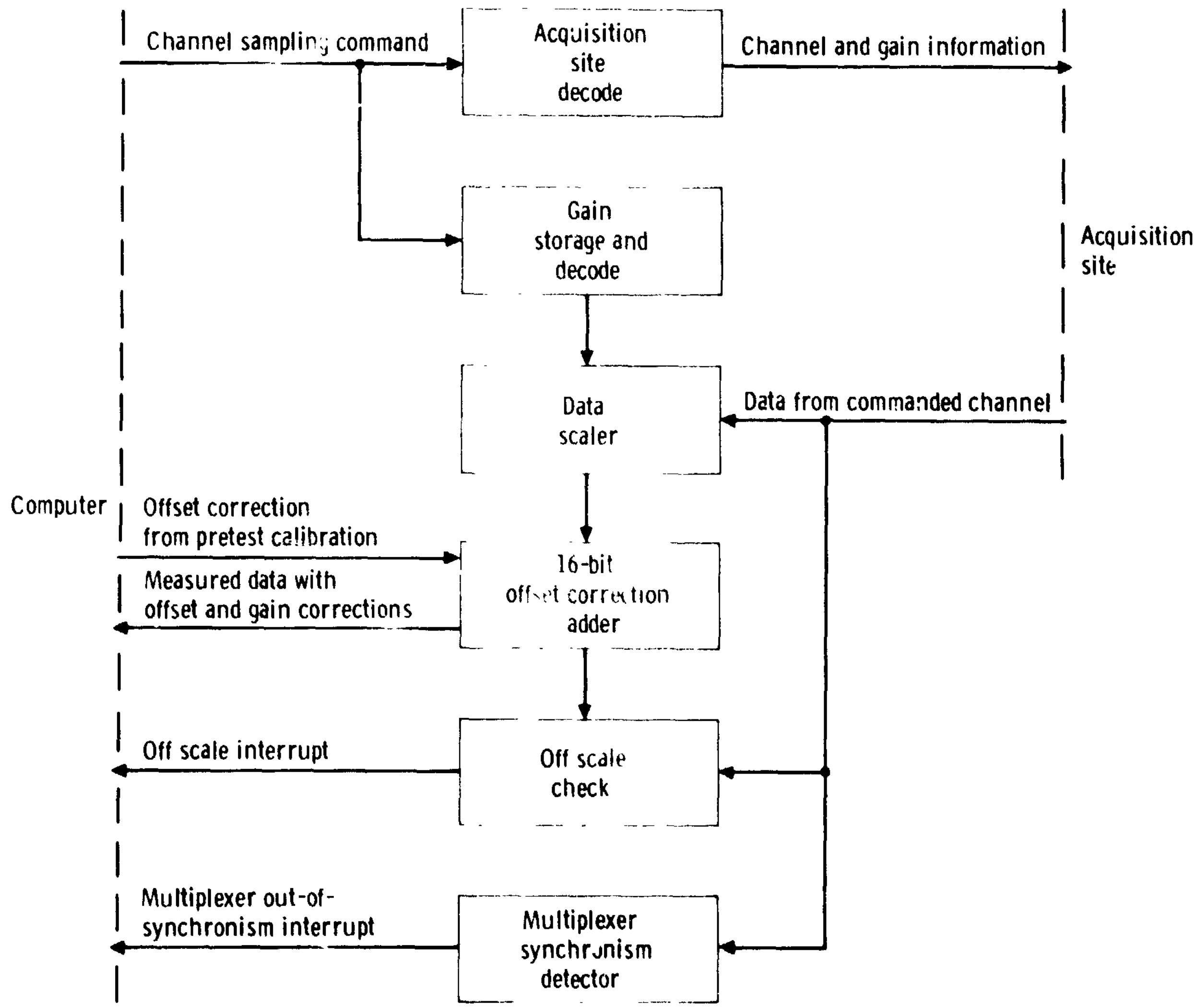

Figure 8. Block diagram of data acquisition interface.

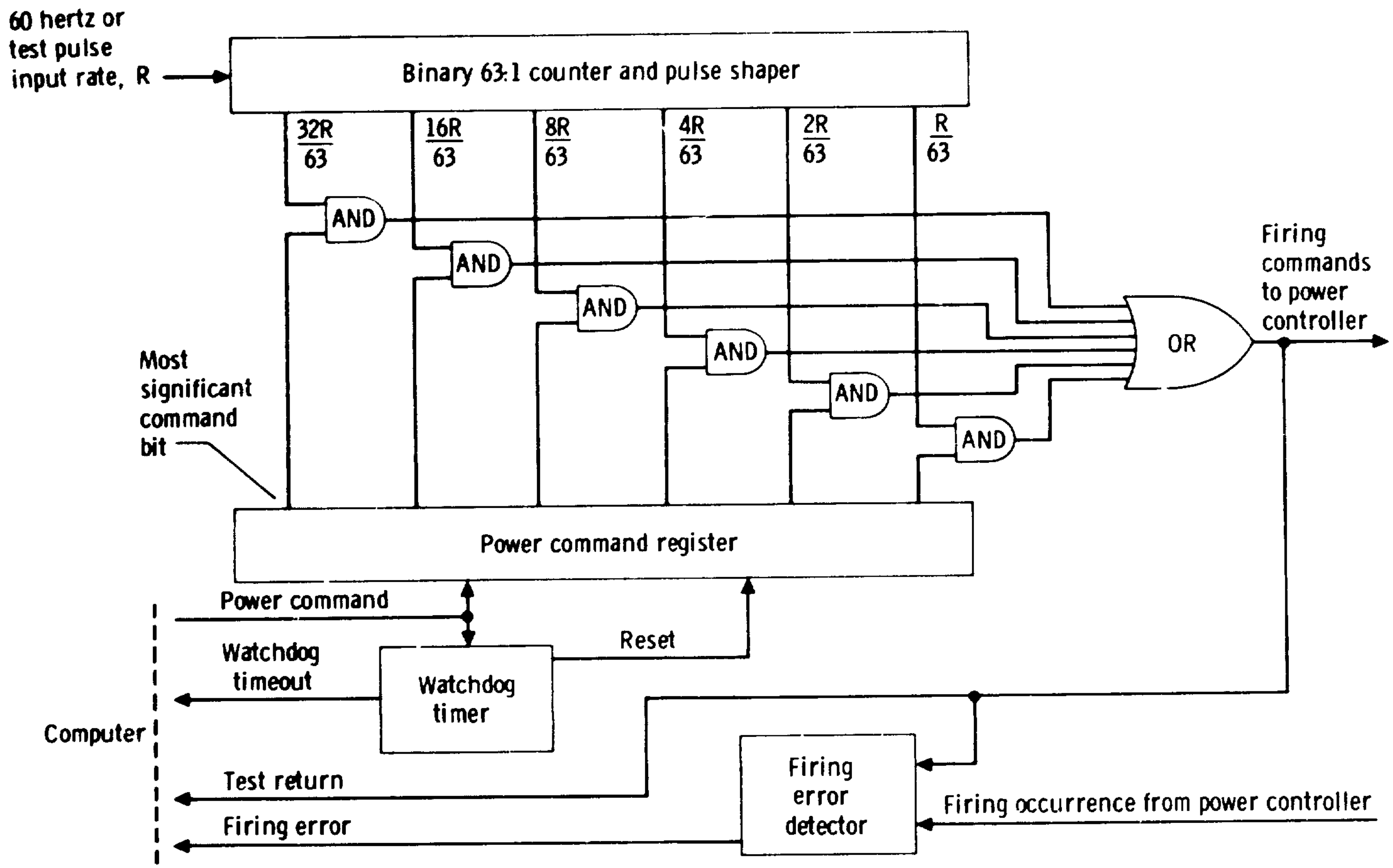

Figure 9. Rate multiplier block diagram.

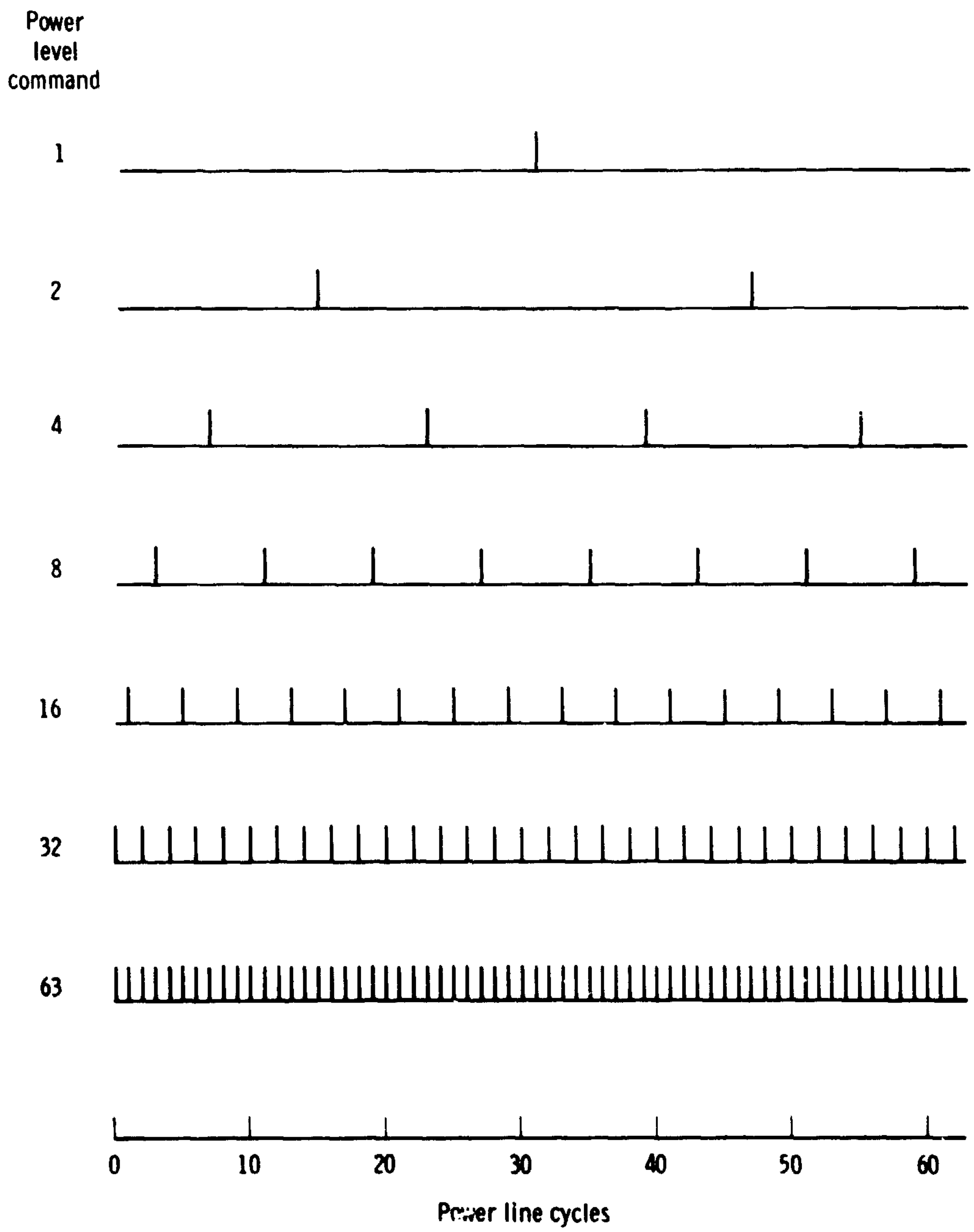

Figure 10. Rate multiplier firing commands produced by various power level commands.

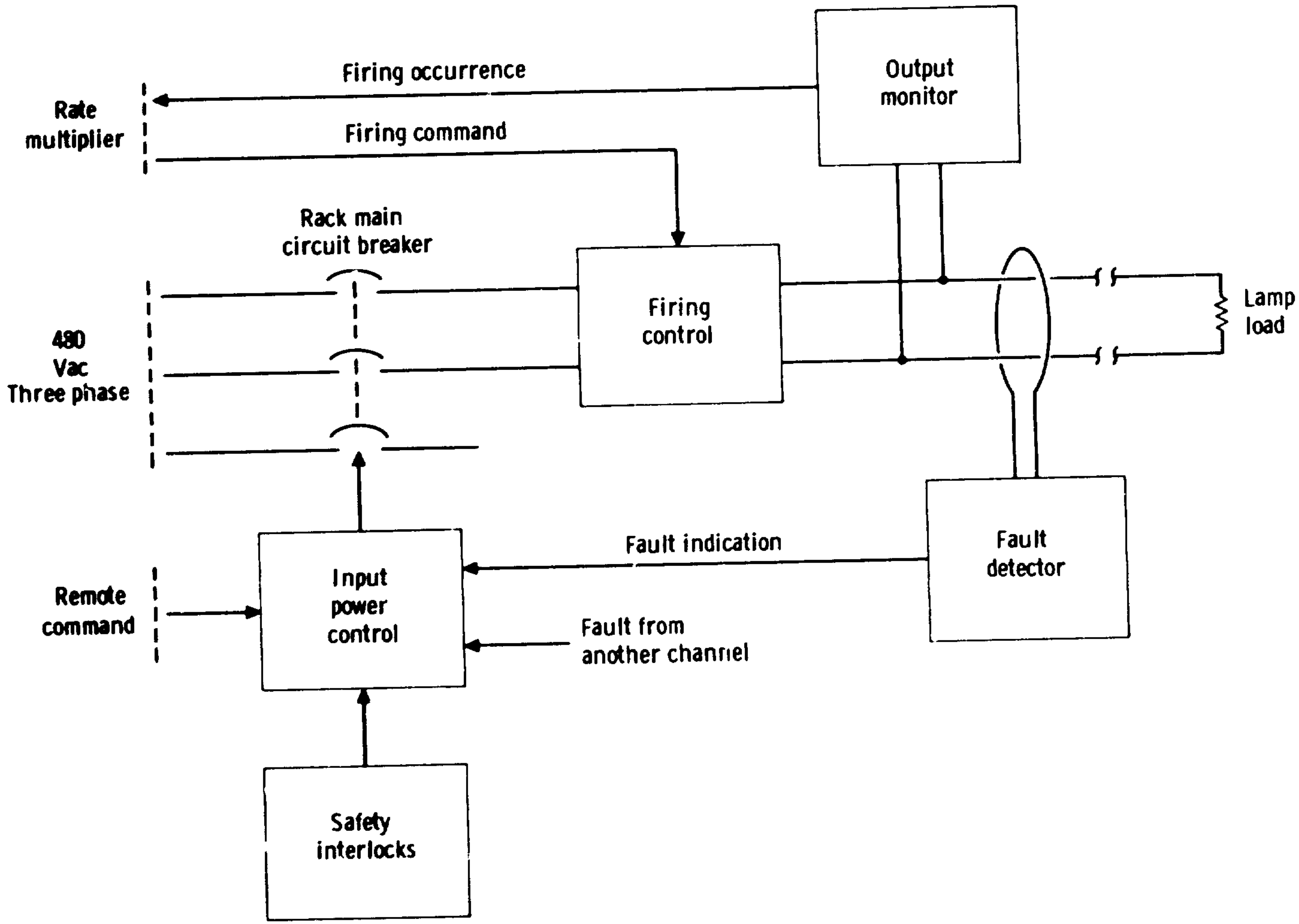

Figure 11. Power controller block diagram.

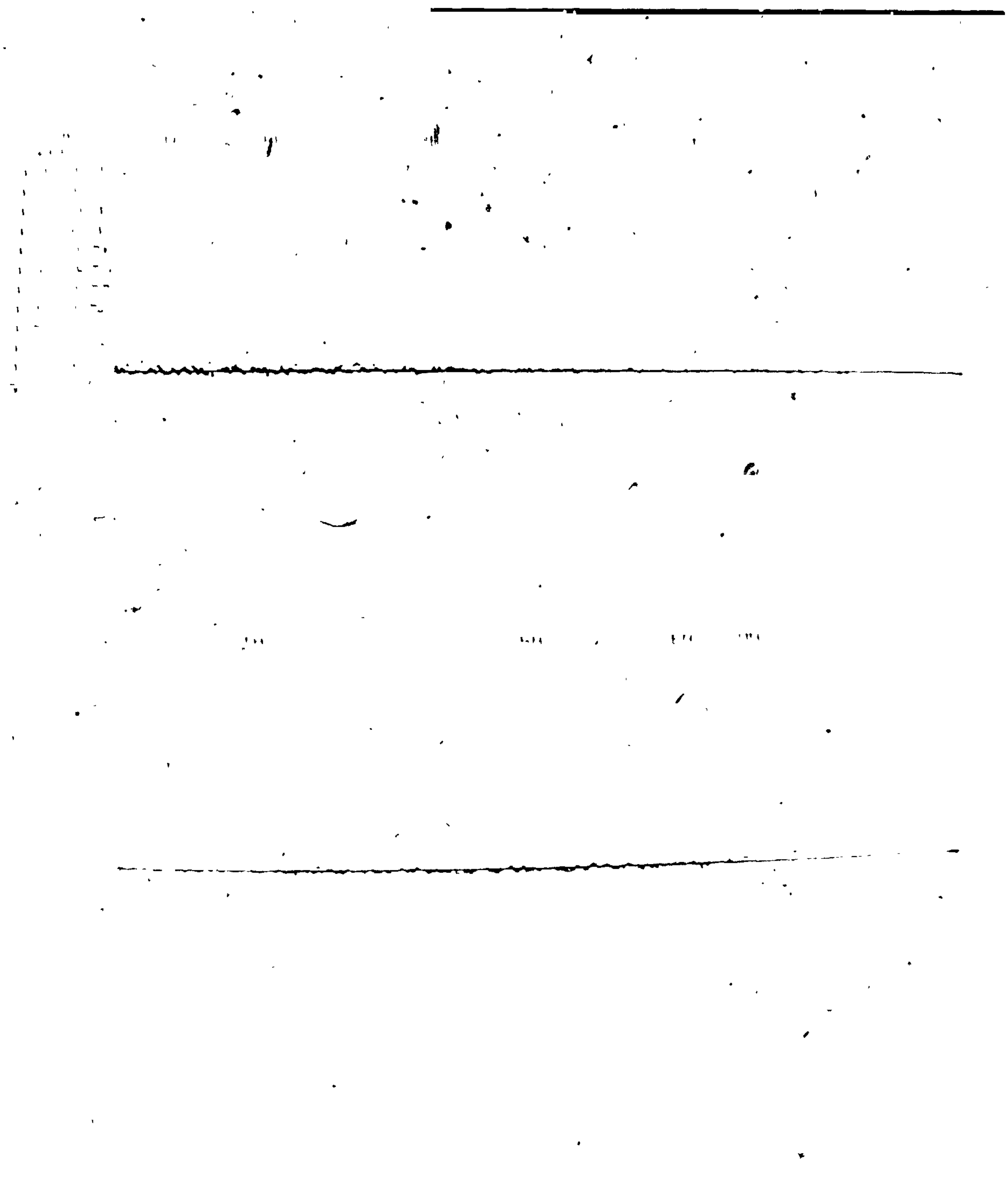

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Figure 12. Control error display.

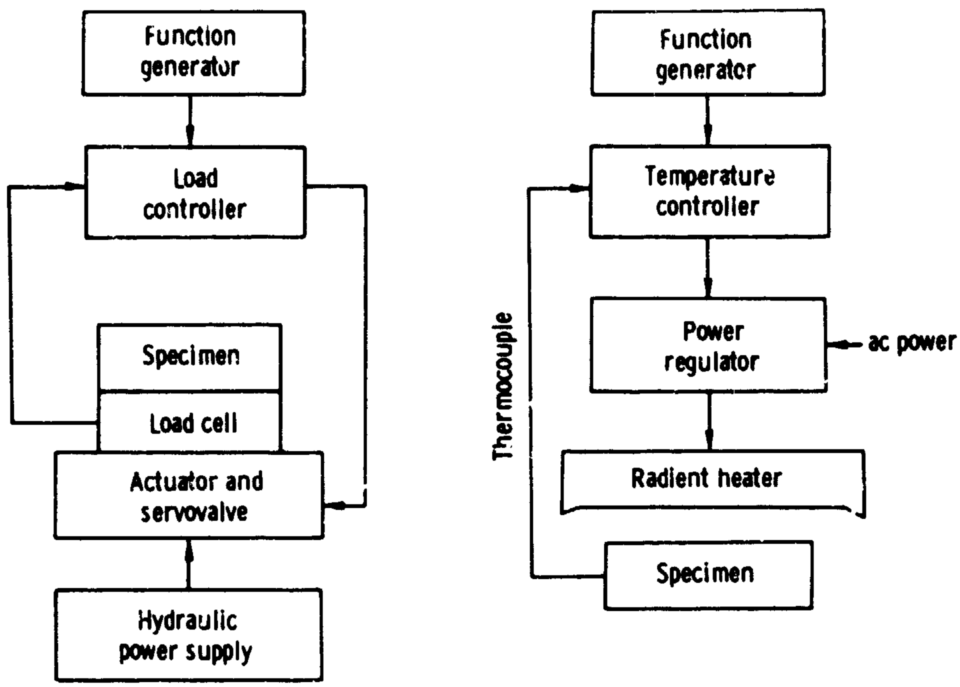

Figure 13. Block diagrams of hydraulic and thermal load control systems.

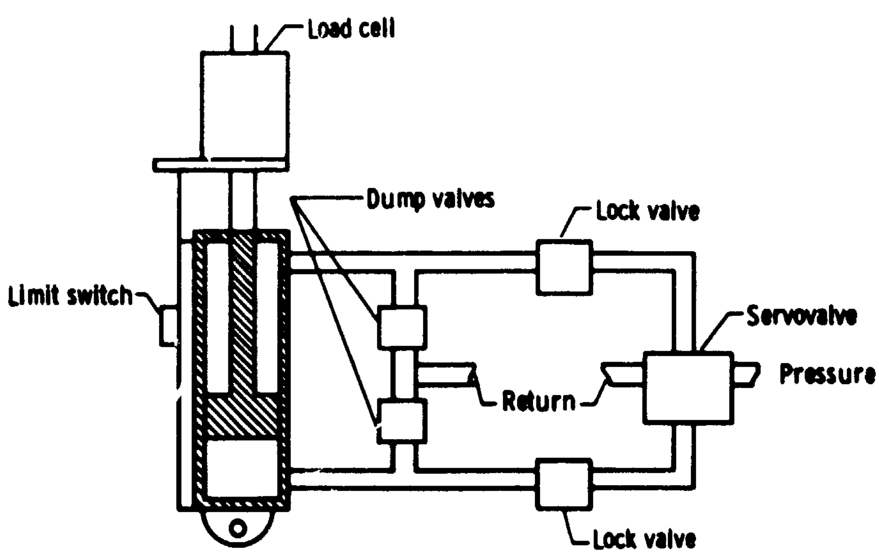

Figure 14. Electrohydraulic fail-safe system.

1. Pump
2. Muffler
3. Filler breather
4. Filler neck
5. Shutoff valve
6. 4-way selector valve
7. Pressure gauge 0 to 34,473 kN/m^2 (0 to 5000 psi)
8. Lubrication control unit
9. Relief valve
10. Air shutoff valve
11. Air gauge 0 to 1103 kN/m^2 (0 to 160 psi)
12. Liquid level indicator
13. Check valve
14. Filter element

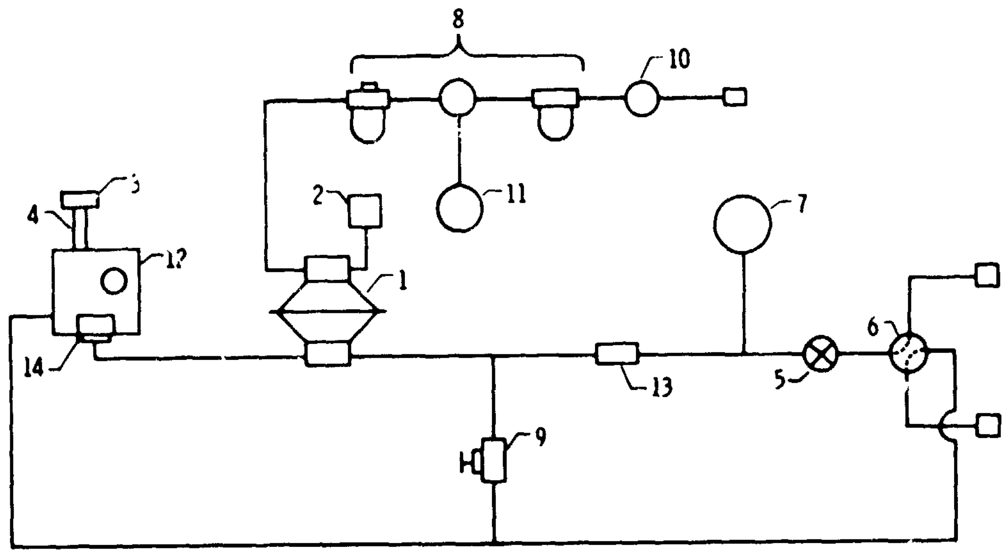

Figure 15. Hydraulic schematic for a portable, manual controlled, air-operated hydraulic loading system.

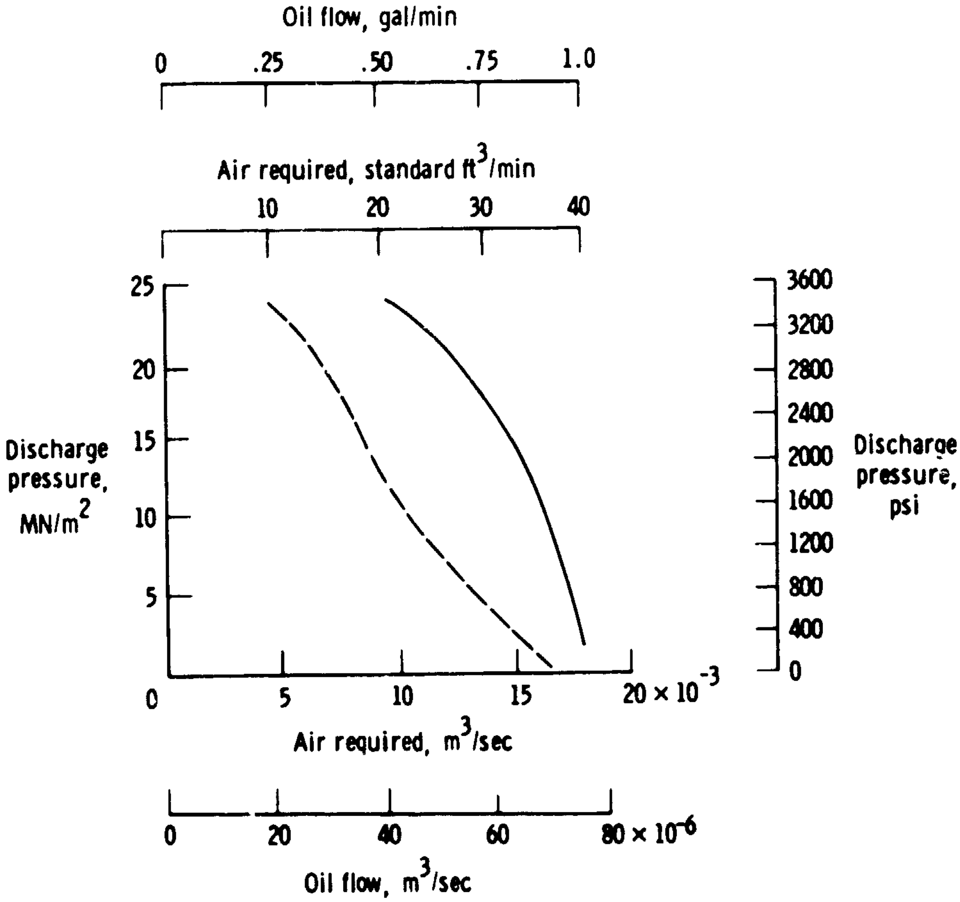

Figure 1.. Air operated hydraulic loading system pressure and flow capabilities.

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Figure 17. Universal electrohydraulic loading testing machine.

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Figure 18. Temperature cycling ovens.

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Figure 19. PA-30 moment of inertia test.

Figure 20. Radial drill press.